Innovations in gradient coil construction

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Gradient coil design involves dealing with both electromagnetic and engineering considerations. In fact the efficiency and size of the imaging region is not the biggest challenge. Rather it is satisfying the requirements for cooling, mechanical strength and radial budget, while still obtaining the desired field profile that poses the challenge. Recent improvements in the algorithms used to produce wire patterns, such as the Boundary Element (BE) Method have opened up new possibilities as far as the electromagnetic design of gradient coils is concerned, mainly due to the ability to specify complex surfaces for current flow and arbitrary field targets. Using several novel design innovations, made possible by these new electromagnetic design tools, we have tackled the problem of building a head gradient coil insert for use at UCAIR, in Salt Lake City.

Methods

We have assembled the parts for the head insert gradient coil with the electromagnet design done using the BE method. The *Z*-axis and its active shield were wound using a Kapton tape insulated wire. This wire has a square cross section of 5.3 mm, with a round 3 mm diameter internal cooling channel. The *Z*-axis is composed of 3 separate layers of windings(2 primary layers and an active shield). These layers provide cooling for the whole system due to water flowing through them. The second primary layer is added to improve the efficiency of the Z-axis of the coil, but also provides extra cooling and a convenient place to mount a transverse axis. Each layer of the Z gradient coil was wound into a square groove machined into a G10 form using a 5 axis CNC cylindrical mill. The elements array of the wire pattern, along with the machined forms and wound Z-layers is shown in Fig 1.

The transverse gradients were constructed using 3/16" copper sheets rolled to fit the outer diameter of the forms holding the *Z*-layer windings. Each "thumbprint" was first annealed, then had the wire pattern machined into it with a 5 axis water-jet CNC cutter, employing a high pressure water flow containing abrasive aluminum oxide grains that readily cut through metal. The two transverse axes were designed to be mounted on each of the inner layers of *Z*-windings. Importantly, the surface used to design the transverse axis using the BE method had a circumferential section of width 5 cm removed along the *Z* direction, that made it possible to run water lines and electrical lines to the *Z*-layers without needing to increase the radial budget, and another excised section through the origin in the *XY* plane of 4 mm extent to separate the wire patterns cleanly, making the construction of the final coil simpler.

The increased space for water lines allowed us to also parallelize the flow through the *Z*-layer windings and increase it by a factor of ~20. This required purpose built water connections that form a manifold for the hollow wire that provides water connections at desired points along *Z*.

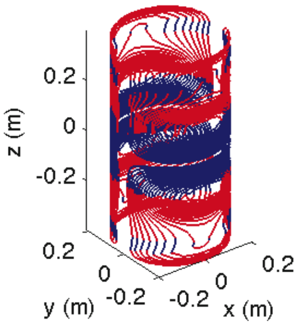

Fig 2: The elements array for the four thumbprints needed for one of the transverse coils. The gaps created in the mesh are clearly seen which allow for electrical and water connections to be made

The final coil will be vacuum potted using an air cycling method that was tested with a small scale model of the coil. By reducing the pressure down to a level just above the vapor pressure of the catalysts in the epoxy, to prevent too much bubbling of the catalyst, the air is removed from the coil and epoxy is drawn in via a tube into a vacuum system. When the coil is full of epoxy the air is allowed in, and the air pressure on the epoxy pushes it into the evacuated voids were pure flow was insufficient. In this way small voids are avoided that can lead to electrical breakdown. Some bubbling of the catalyst occurs in the top couple of cm's after vacuum potting, which makes it desirous to limit any close positioning of electrical connections in the top of the coil.

Conclusions

Use of the BE method allows us to design on multiple surfaces, create shields, create gaps in the current flow where we can place other hardware. Furthermore it is fast, reliable and easy to use. Using advanced EM design tools such as the BE method allows the innovations discussed to be included directly in the electromagnetic design, keeping it optimal. Vacuum potting of the resulting coil is essential to eliminate high voltage breakdowns and to hold everything in place so that the coil is not weakened mechanically during operation. These construction and design techniques are applicable to many magnets used in MRI such as small animal gradient inserts and dreMR field cycling magnets..

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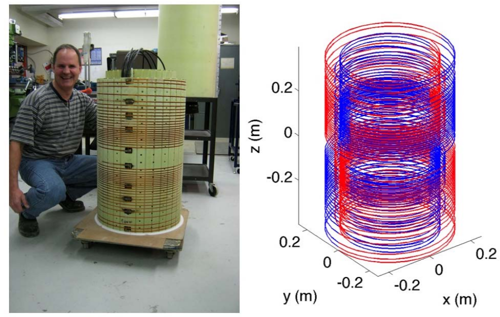

Fig 1: The three layers of the *Z* axis in the machine shop, ready for potting, the outer form with wheels is behind. The current elements produced by the BE method are show how faithfully we can mechanically produce our EM design.

Fig 3: The innermost winding of the *Z* coil is shown with the thumb prints for the *Y* axis during mounting.

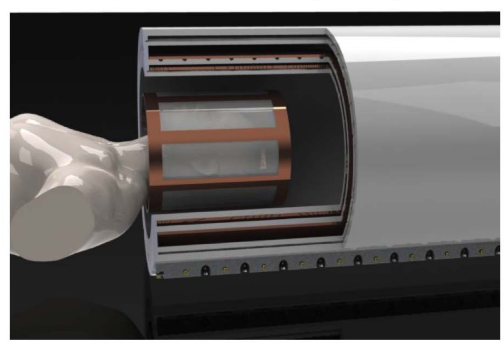

Fig 4: The full design with a human head and RF coil included to show how the final system will look. A section has been removed from the CAD drawing to allow the interior of the coil to be seen.

References

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